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TEMPERATURE MEASUREMENTS WITH THERMOCOUPLES IN COMBUSTION GASES

W.Alvermann and P.Stottmann

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TEMPERATURE MEASUREMENTS WITH THERMOCOUPLES IN COMBUSTION GASES

(Catalytic Effects - Required Data Corrections)

W.Alvermann and P.Stottmann

German Research Institute for Aeronautics and Space (DFL)

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For temperature measurements in combustion gases by means of thermocouples, corrections are suggested for compensating the errors due to the velocity of the medium, radiation, and heat conduction. The possible errors by catalytic effects when using thermocouples of noble metals are studied. Experimental results for different probes show that the corrected values are in good agreement. A method is described for electrically eliminating the radiation error by a resistance heating. The data corrections are tabulated, and the temperature data are plotted for various thermocouples. Author

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1. Introduction /7

In investigations on jet power plants it is necessary to make accurate local temperature measurements in the gas jets. Since measuring methods without the use of probes will yield data on the temperature profile only under extremely ideal experimental conditions, the use of a pyrometer of some type is indispensable. In the temperature range up to 2000° K, primarily thermocouples are used as thermoelectric data transmitters. Here, noble metal thermocouples (for example, PtRh/Pt and IrRh/Ir) are used since they best meet the requirements made on thermels for use in measurements within flame gases (Bibl.1), specifically, chemical stability, mechanical strength, high melting point. However, it must always be taken into consideration that errors of measurement, produced by catalytic effects, may occur in noble-metal thermocouples.

Since, with respect to temperatures in flowing gases, a differentiation must be made between static and total temperature, a static temperature probe is generally used for the measurements, in which the velocity of the gas is "stagnated" to a low velocity ($w < 0.1$ Mach). A complete stagnation of the gas, however, must not take place since this would cause the gas to cool, due to heat exchange with the wall of the probe. In addition to the influence of the gas velocity on the measuring accuracy, a point to be taken into consideration is the error of measurement produced by heat dissipation and radiation.

In this report, we will describe the procedure for a test-data correction in temperature measurements with thermels. Simultaneously, we will attempt to answer the question whether, in addition to the instrument errors, errors might be produced by catalytic effects when using noble-metal thermocouples.

2. Notations /8

A	(m^2)	= Area
R	($\frac{\text{kp-m}}{\text{kg deg}}$)	= Special gas constant
Q	(kcal)	= Heat quantity
T	($^\circ$K)	= Temperature
Re	(/)	= Reynolds number
Ma	(/)	= Mach number
Nu	(/)	= Nusselt number
Pr	(/)	= Prandtl number
C_s	($\frac{\text{kcal}}{m^2 \text{ hr deg}^4}$)	= Black-body radiation constant

c_p $\left(\frac{kcal}{kg\ deg}\right)$ = Specific heat capacity at constant pressure

d (m) = Diameter

g $\left(\frac{m}{sec^2}\right)$ = Acceleration of gravity

p $\left(\frac{kp}{m^2}\right)$ = Pressure

ℓ (m) = Length

α $\left(\frac{kcal}{m^2\ hr\ deg}\right)$ = Heat transfer coefficient

ϵ (/) = Emissivity

$\varkappa$ (/) = Adiabatic exponent /9

ρ $\left(\frac{kg}{m^3}\right)$ = Density

η $\left(\frac{kg\text{-}sec}{m}\right)$ = Dynamic viscosity

ν (m^2/sec) = Kinematic viscosity

3. Catalytic Effects in Measurements with Noble-Metal Thermocouples /10

3.1 Catalytic Activity of Some Noble Metals

The catalytic activity of some noble metals (for example, platinum, palladium, iridium) in many chemical reactions - for example, hydrogenation reaction, ammonia oxidation - is well known. Under the influence of surface forces, produced by these metals, a molecular degradation takes place already at low temperatures. This effect can be explained by an activation of the hydrogen or oxygen, absorbed by the noble metal.

In air-breathing engines, working with hydrocarbons as fuel, gas mixtures are present whose reactions can be initiated or accelerated under the influence of catalysts. Thus, in measuring the temperature of these gases by means of noble-metal thermels there is the danger that, because of catalytic effects, certain reactions, in which thermal energy is liberated, are released at the probe. This increases the temperature of the probe so that the indicated temperature no longer corresponds to the gas temperature prevailing at the test point. Consequently, before using noble-metal thermocouples, a check test must be run to determine whether the result might be falsified by catalytic effects. This is specifically the case in investigations on combustion chambers of jet engines, in which a noble-metal thermel is most suitable for local temperature measurements, for mechanical and thermal reasons.

This raises the question as to the type of gas mixture and the degree of temperature at which catalytic effects must be expected.

3.2 Catalytic Effects at Temperatures below the Ignition Temperature of the Fuel-Air Mixture

At temperatures below the ignition temperature of a mixture of fuel ($C_n H_m$) and air, there is no doubt that reactions are released due to the catalytic effect of a PtRh/Pt or IrRh/Ir thermocouple. Gas mixtures of this type exist in the mixing zone within the combustion chambers of jet engines, at the point at which the injected fuel mixes with air and with the refluxing combustion /11
gases.

Using the test setup shown in Fig.1, measurements were made with PtRh/Pt and IrRh/Ir thermels. First, fuel (JP-1) was introduced into the cold (room temperature) air stream of the combustion chamber 2, and the temperature of the mixture was then measured. No catalytic effects were detected. Since the fuel was still present in droplet form in the mixture, the hot junction of the thermocouple was cooled so much that a temperature rise, produced by the possibly liberated heat of reaction, was not detectable.

By preheating the air to about 300° - 600°C in the combustion chamber 1, it was clearly demonstrated that the use of PtRh/Pt and IrRh/Ir thermels induced reactions, due to the catalytic effect of the noble metals. The liberated heat of reaction led to a heating of the hot junction, so that the indicated thermoelectric potential no longer could be considered a criterion for the gas temperature. The experiments were conducted as follows: The air in the combustion

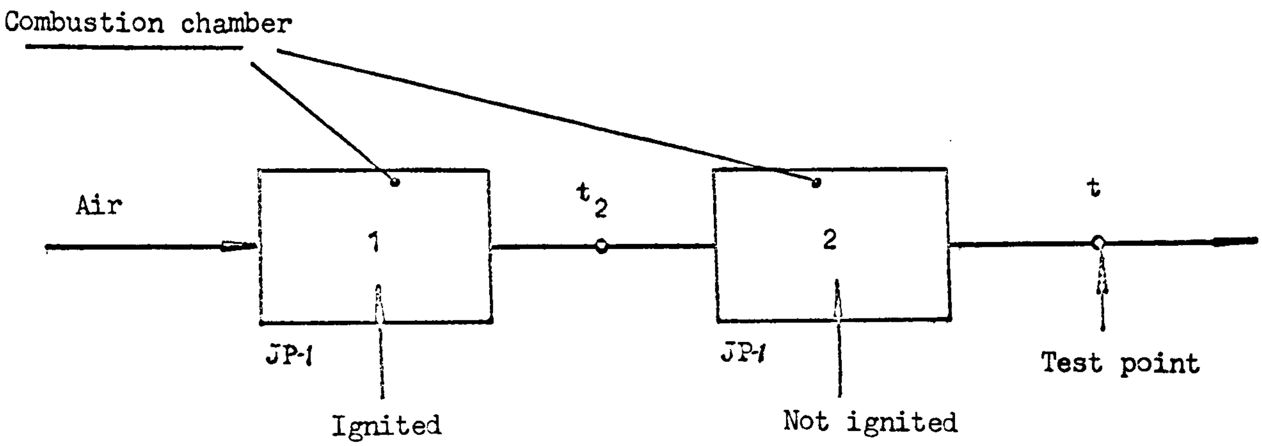

Fig.1 Test Setup for Detection of Catalytic Effects

chamber 1 was heated until, on entry into the combustion chamber 2, the temperature of this was just below the ignition temperature of the gas mixture used (JP-1 $\sim 650^\circ$ C, at a gas velocity in the combustion chamber of about 80 m/sec). Then, various amounts of fuel were injected into the combustion chamber 2. At the outlet of the combustion chamber 2, the temperature was measured with a noble-metal thermel and with a NiCr/Ni thermocouple.

Figure 2 shows the indicated temperature, as a function of the fuel-air ratio. Since no combustion took place in the combustion chamber 2, whereas the injected fuel removed heat of evaporation from the air, the data obtained with the NiCr/Ni thermocouple showed the expected course of the gas temperature. The values obtained with a noble-metal thermel (PtRh/Pt and IrRh/Ir), however, /12

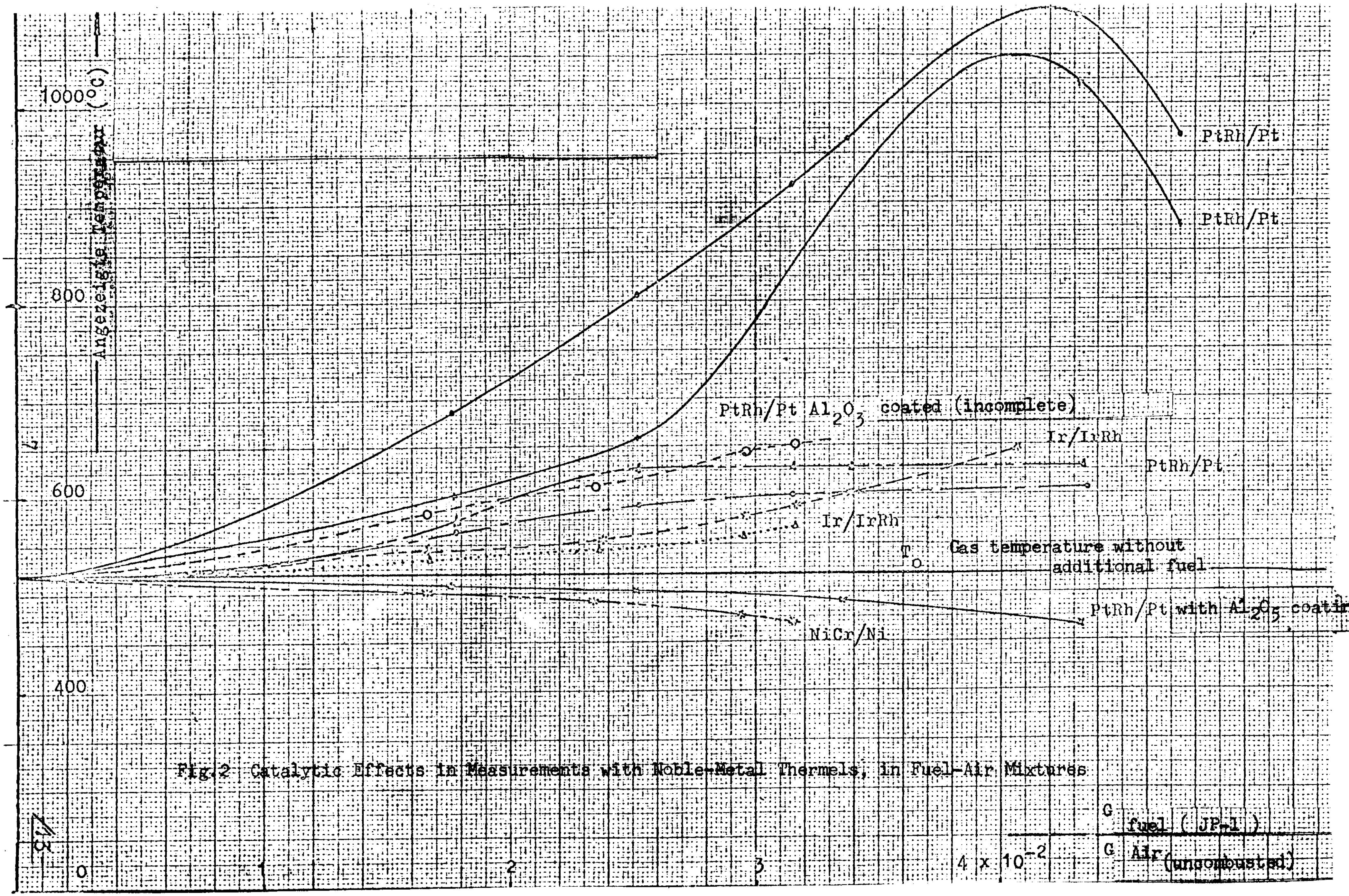

Fig. 2 Catalytic Effects in Measurements with Noble-Metal Thermels, in Fuel-Air Mixtures

deviated greatly from the above result and showed much higher temperatures. As determined also optically, a combustion took place at the noble-metal junctions, presumably due to the catalytic activity of the noble metals. The data obtained with PtRh/Pt and IrRh/Ir thermocouples were not reproducible. The reason most likely is a change in surface condition (contamination) of the hot junction, especially since a cleaning of this junction - i.e., an increase in the catalytically active area - resulted in a considerably higher temperature reading.

A confirmation for the assumption that the reactions on the thermocouples - and thus also the errors of measurement - were due to the catalytic activity of the noble metals, was obtained in the following manner: The noble-metal wires were coated with Al_2O_3. This caused the measured values to become the same as those obtained with a NiCr/Ni thermocouple. In these experiments, it was found that only an integral coating of Al_2O_3, preventing any direct contact between gas and metal, is a guarantee for preventing erroneous measurements due to catalytic effects (see Fig.2).

Consequently, in investigations on combustion chambers of air-breathing engines, no uncoated PtRh/Pt or IrRh/Ir thermocouple must be used in the mixing zone and in determining the transition from the mixing zone to the reaction zone, in which the fuel reacts with the oxygen, because of the fact that catalytic effects will falsify the test result. The magnitude of the catalytic effect increases with the temperature, up to the spontaneous-ignition point of the mixture, and is dependent on the fuel-air ratio at the test point. Furthermore, there is also a dependence on the prevailing surface condition of the thermocouple wires, so that the magnitude of the effects is not reproducible. When using noble-metal thermocouples, catalytic effects in gas mixtures of un- /14 burned hydrocarbons and oxygen can be prevented by coating the wires with Al_2O_3.

Of course, in the above investigations, it is still necessary to check whether the probe itself may act as a mechanical obstruction of the flame and thus influence the position of the reaction front.

3.3 Catalytic Effects at Temperatures above the Ignition Temperature of Explosive Fuel-Air Mixtures

In a hydrocarbon-air mixture, to which the activation energy is supplied by heat conduction, the influence of the catalytic effect of the noble metals is no doubt dependent on the combustion velocity. It can be assumed that, at a low combustion rate, the catalytic activity of the metals accelerates the reactions. In an explosive mixture, in which the reactions take place spontaneously without catalytic influence, it cannot be expected that the reactions on the noble-metal thermocouples are intensified. In the reaction zones of combustion chambers of jet engines in which high combustion velocities prevail, erroneous measurements due to the catalytic effects are hardly expected. This assumption was confirmed by measurements with uncoated PtRh/Pt thermocouples and by comparative measurements using probes with gastight Al_2O_3 coatings, in an experimental combustion chamber.

In gases in which hydrogen or carbon monoxide is present in such low concentrations compared to the air, that the mixture is not explosive, it must be expected that the above noble metals act as active catalysts. Consequently, in measuring the temperature at the outlet of a combustion chamber there exists the danger that, at incomplete combustion of the fuel (C_nH_m), an aftercombustion takes place on the noble-metal thermel which will result in erroneous measurements. Naturally, in addition to the heat liberated per unit time at the hot junction, the heat transfer coefficient α, which is decisive for the transfer of the heat of reaction to the gas, determines the difference between the temperature of the thermel and the temperature of the gas.

In the investigations, described in Section 6, no catalytic effects of /15 this type could be found. The difference between the test results, when using an uncoated and an Al_2O_3-coated PtRh/Pt thermocouple, could be attributed to the measurement error produced by the differing heat emission.

3.4 Catalytic Effects in a Reducing Atmosphere

During pyrometry in reducing gases, when using a noble-metal thermocouple, no erroneous measuring results due to exothermal catalytically-induced reactions at the hot junction are expected. However, because of the active catalysts, the reduction of oxides may be initiated or accelerated, causing the liberation of corrosive elements which, under formation of compounds, migrate along the grain boundaries into the noble metals. This results in a change of the thermoelectric properties and an embrittlement of the wires. In the case of PtRh/Pt thermocouples, the main responsible factors for a shortening of the thermocouple life are, specifically, the elements phosphorus, silicon, and sulfur released from the ceramics of the protecting tube or from the gas by reduction.

4. Required Data Corrections in Measurements with a Static Temperature Probe /16

4.1 Systematic Error of Measurement in Thermometry with Thermocouples

In local temperature measurements in gases, the thermoelectric data pickup indicates the temperature of the probe (i.e., in the case of thermocouples, the temperature of the hot junction). This temperature is not identical with the gas temperature to be measured. The difference between the indicated and the total temperature of the gas is due to the following instrument errors:

a) At the hot junction of the thermocouple, the kinetic energy of the gas is not completely converted into thermal energy (recovery factor).

b) The heat dissipation and

c) the heat emission by the hot junction result in a temperature drop of the measuring element.

To eliminate the influence of the gas velocity to the greatest possible extent, a static temperature probe (as shown in Fig.3), in which the velocity of the gas is reduced, is generally used.

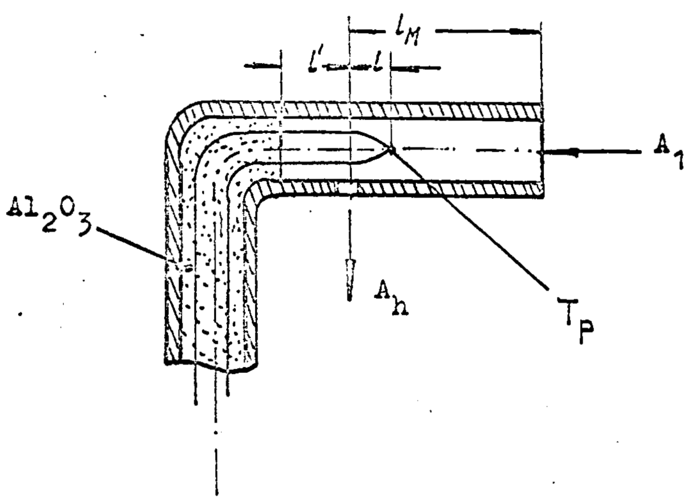

Fig.3 Static Temperature Probe

The possibility of keeping the dissipation and radiation error to a /17
negligible magnitude by structural measures, such as an increase in the length of the thermocouple exposed to the hot gas or the attachment of radiation shields, can be realized only in part because of the high thermal and mechanical loads above 1500° C, due to material reasons. Therefore, it is necessary in most

cases to perform a data correction. The total correction, as the sum of individual corrections, will be

$$\Delta T_{corr} = \Delta T_w + \Delta T_{rad} + \Delta T_{diss} , \tag{4.1}$$

where

ΔT_w = correction for velocity;

ΔT_{rad} = correction for radiation;

ΔT_{diss} = correction for dissipation.

4.2 Determination of the Velocity Correction

Since not all of the kinetic energy on the thermel is converted into thermal energy, the following relation, according to definition, is valid:

$$\frac{\Delta T_w}{T_{tot} - T_{s1}} = \frac{T_p - T_{s1}}{T_{tot} - T_{s1}} = r \text{ (recovery factor)} . \tag{4.2}$$

The magnitude of the recovery factor depends on the layout of the probe and on the state of the flow. When using a static temperature probe, of the type shown in Fig.3 in which the thermocouple wires are arranged parallel to the direction of flow, the recovery factor will be $r \approx 0.86 \pm 0.09$ (Bibl.2) within the region of Mach 0.1 to Mach 1.0.

The static gas temperature (T_{s1}) in the probe, as shown in Fig.3, is obtained from the relation

$$T_{tot} - T_{s1} = \frac{w_1^2}{2c_p} \tag{4.3}$$

or

$$\frac{T_{tot} - T_{s1}}{T_{s1}} = \frac{1}{2} (\varkappa - 1) Ma_1^2 . \tag{4.3a}$$

Thus, the following expression is obtained for the velocity correction: /18

$$\Delta T_w = T_{tot} (1 - r) \frac{\frac{1}{2} (\varkappa - 1) Ma_1^2}{1 + \frac{1}{2} (\varkappa - 1) Ma_1^2} . \tag{4.4}$$

The gas velocity w_1, required for determining of Ma_1, is obtained, at a total temperature T_{tot}, from

$$w_0 = \sqrt{\frac{2\kappa}{\kappa - 1} R \cdot T_{tot} \left(1 - \left(\frac{p_0}{p_{tot}}\right)^{\frac{\kappa - 1}{\kappa}}\right)} \tag{4.5}$$

with $T_{tot} = T_p + \Delta T_{corr}$, estimated.

Using the continuity equation

$$w_1 \cdot \rho_1 \cdot A_1 = w_h \cdot \rho_h \cdot A_h$$

and the assumption that, in the vents of the probe (A_h), the same static pressure p_0 and thus also the same velocity as in the free jet prevail, the following expression is obtained for the gas velocity (w_1) in the probe:

$$w_1 = w_0 \frac{\rho_h \cdot A_h}{\rho_1 \cdot A_1} = w_0 \cdot \frac{p_0}{p_{s1}} \cdot \frac{T_{s1}}{T_{r\ ex}} \cdot \frac{A_h}{A_1} .$$

Using the adiabatic relation

$$\frac{T_{s1}}{T_{r\ ex}} = \left(\frac{p_{s1}}{p_0}\right)^{\frac{\kappa - 1}{\kappa}} ,$$

we obtain

$$w_1 = w_0 \left(\frac{p_0}{p_{s1}}\right)^{\frac{1}{\kappa}} \cdot \frac{A_h}{A_1} . \tag{4.6}$$

Since the static pressure p_{s1} in the probe is not known, the quantity w_1 is first calculated under the assumption that the total pressure and the total temperature prevail within the probe.

This will yield /19

$$w_1 = w_0 \left(\frac{p_0}{p_{tot}}\right)^{\frac{1}{\kappa}} \cdot \frac{A_h}{A_1} . \tag{4.7}$$

The possible correction for the assumption is obtained by iteration, using eq.(4.3) and the following relation:

$$\frac{p_{si}}{p_{tot}} = \left(\frac{T_{si}}{T_{tot}}\right)^{\frac{\kappa}{\kappa - 1}} \tag{4.8}$$

4.3 Determination of the Radiation Correction

The thermocouple, in the static temperature probe, is in radiative exchange with the inside wall of the probe. The magnitude of the error of measurement, produced by the heat transfer by radiation, is obtained on the basis of the Stefan-Boltzmann law of total radiation:

$$\Delta T_{r,ad} = \frac{1}{\frac{1}{\epsilon_p} + \frac{A_p}{A_{wi}}\left(\frac{1}{\epsilon_{wi}} - 1\right)} \cdot \frac{C_s}{\alpha_p}\left(\frac{T_p^4}{100^4} - \frac{T_{wi}^4}{100^4}\right) \tag{4.9}$$

Here, ϵ_p is the emissivity of the thermocouple wires, ϵ_{wi} is the emissivity of the inside wall of the probe, and $C_s = 4.96 \frac{\text{kcal}}{\text{m}^2 \text{ hr deg}^4}$ is the black-body radiation constant. The quantity A_p is the area of the thermocouple, decisive for the radiative exchange, and A_{wi} is the corresponding area of the diffusely radiating inside wall of the probe (Bibl.3).

If the area of the inside wall of the probe is much larger than the area of the thermocouple, practically only the radiation factor of the thermocouple is decisive for determining the radiation correction. We then obtain

$$\Delta T_{r,ad} = \frac{\epsilon_p \cdot C_s}{\alpha_p}\left(\frac{T_p^4}{100^4} - \frac{T_{wi}^4}{100^4}\right) \tag{4.9a}$$

The temperature T_{wi} of the inside wall of the probe must be measured or else, by means of a heat balance, determined from the measured temperature of /20
the outside wall. For determining the heat transfer coefficient α_p, the flow conditions at the hot junction of the thermel must be determined. The Reynolds

number is obtained from the relation

$$Re = \frac{w_1 \cdot d_p}{\nu} = \frac{w_1 \cdot \rho_1 \cdot d_p}{\eta} . \qquad (4.10)$$

It is suggested to use here the formula with the dynamic viscosity, since the kinematic viscosity ν is generally tabulated only for 1 atm. The density ρ of the flow medium is obtained from the mean temperature between gas and wall:

$$\rho_1 = \frac{p_1}{R \cdot \frac{1}{2} (T_{s1} + T_p)} . \qquad (4.11)$$

Under the assumption that no dissociation takes place, the following relation is valid, according to McAdams, for a spherical relative flow at Reynolds numbers of 20 to 150,000:

$$Nu = 0.33 \; Re^{0.6} . \qquad (4.12)$$

If the hot junction of the thermocouple does not have a spherical shape, then, for the case of blunt-welded thermocouple wires, the equation by Scadron and Warschawsky (Bibl.2)

$$Nu = (0.085 \pm 0.009) \; Re^{0.674} \qquad (4.12a)$$

can be used, which is valid for round wires exposed to longitudinal flow. Here, the Reynolds number and the Nusselt number must be referred to the wire diameter d, and the physical constants must be referred to the total temperature T_{tot} of the gas. Equation (4.12a) is valid for Reynolds numbers of 100 - 10,000.

Using the Nusselt number, the heat transfer coefficient will be

$$\alpha_p = \frac{Nu \cdot \lambda}{d_p} \qquad (4.13)$$

where λ is the thermal conductivity of the gas.

4.4 Determination of the Dissipation Correction /21

In determining the error of measurement, produced by heat dissipation, the thermocouple wires are considered as cylinders with a length ℓ and a diameter d, whose tips have the temperature T_p of the hot junction of the thermocouple and whose toes have the temperature T_0. The surface of these cylinders, in accordance with the heat transfer coefficient α_p, is supplied with heat from the gas, at a temperature T_{tot}. If the heat supply at the frontal area is neglected, the following expression is obtained for the dissipation correction:

$$\Delta T_{diss} = (T_{tot} - T_0) \frac{1}{\cosh (a \cdot \ell)} \tag{4.14}$$

with

$$a^2 = \frac{4\,\alpha_p}{\lambda_{th} \cdot d} ,$$

where λ_{th} is the thermal conductivity of the thermocouple wire.

When using a static temperature probe (Fig.3), the length ℓ must be substituted by the distance between the hot junction and the vents, since an approximately constant heat transfer coefficient can be expected only for this particular segment. Consequently, the toe temperature T_0 is the temperature of the thermowire at the level of the vents. However, in most cases, this temperature cannot be measured. If the immersion depth of the uncooled probe into the hot gas is large with respect to the diameter, the error of measurement due to heat dissipation is usually negligibly small (see Section 8). The order of magnitude of the dissipation error, according to eq.(4.14), is obtained on substituting the temperature T_0 by the temperature of the inside wall of the probe (T_{wi}). If the temperature of the thermowires T_w, at the inlet to the protecting tube, is known (distance from the hot junction: $\ell + \ell'$), a more accurate determination of the dissipation correction can be obtained by means of the relation

$$\Delta T_{diss} = \frac{T_{tot} - T_w + (T_{tot} - T'_{tot})(\cosh(a'\ell') - 1)}{\cosh(a\cdot\ell)\cosh(a'\ell')(1 + \frac{a}{a'}\tanh(a\ell)\tanh(a'\ell')} \qquad (4.15)$$

with

$$a^2 = \frac{4\alpha}{\lambda_{th}\cdot d} \text{ and } a'^2 = \frac{4\alpha'}{\lambda_{th}\cdot d} .$$

Here, it is assumed that, over the length ℓ, heat is supplied to the thermo- /22
wires from the gas at a temperature T_{tot}, in accordance with a heat transfer coefficient α whereas, over the length ℓ', heat exchange with the gas of a temperature T'_{tot}, in accordance with a heat transfer coefficient α', takes place. In eq.(4.15), the heat transfer along the frontal area has again been neglected.

4.5 Checking the Data Correction by Heat Balance

A possibility of checking the test data is given by calculating the heat balance for the probe head. Let us consider here, for the case of a static temperature probe of the type shown in Fig.3, the probe wall of a length ℓ_M from the gas inlet to the vents. This segment of the probe jacket receives a radiation energy $Q_{r\ ex}$ from the external flow and an energy by convective heat transfer of $Q_{c\ ex}$ as well as an energy $Q_{c\ in}$, transferred from the internal flow by convection. In addition, this segment receives the thermal energy $Q_{r\ th}$ by radiation from the thermocouple. These amounts of heat must be in equilibrium with the amounts of heat dissipated by radiation Q_r and by dissipation Q_{diss}. The balance then will read

$$Q_{r\ ex} + Q_{c\ ex} + Q_{c\ in} + Q_{r\ th} = Q_r + Q_{diss} . \qquad (4.16)$$

Because of the restricted accuracy of heat-transfer calculations, this equation cannot be used as a determinant equation for the real temperature prevailing at the test point. However, the equation yields a possibility to check whether the order of magnitude of the data correction had been correct or whether the result had been falsified by instrument errors of measurement (for example, catalytic effects).

For the energy, supplied to the probe casing from the gas jet by radiation, the following is valid:

$$Q_{ex} = \epsilon_{tot} \cdot \epsilon_M \cdot C_s \cdot \frac{T_s^4}{100^4} \cdot A_M . \tag{4.17}$$

The static temperature of the gas is obtained from the relation

$$T_s = T_{tot} \left(\frac{p_0}{p_{tot}}\right)^{\frac{\varkappa - 1}{\varkappa}} . \tag{4.18}$$

The heat, convectively dissipated toward the outside of the protecting tube /23 is

$$Q_{ex} = \alpha_{c\,ex} \cdot A_M (T_s - T_{wo}) . \tag{4.19}$$

Since the same conditions exist on the outer surface of the protecting tube as on the plate exposed to longitudinal flow, the following expression is obtained according to Jürges and Merkel (Bibl.4) for the Nusselt number in the case of turbulent flow:

$$Nu = \frac{\alpha_{c\,ex} \cdot \ell_M}{\lambda} = 0.057\ Re^{0.78} \cdot Pr^{0.78} \tag{4.20}$$

or, according to E.Schmidt (Bibl.5), for velocities of $w > 5$ m/sec,

$$Nu = \frac{\alpha_{c\,ex} \cdot \ell_M}{\lambda} = 0.075\ Re^{0.75} \cdot Pr^{0.75} . \tag{4.20a}$$

The physical constants in these equations refer to the mean value of the gas temperature and of the wall temperature. In gas flows of high velocity, in which the heat produced by friction can no longer be neglected, the static temperature T_s must be replaced by the characteristic temperature T_e (Bibl.3, 6):

$$T_e = T_s \left(1 + \sqrt{Pr}\,\frac{\varkappa - 1}{2}\,Ma^2\right) . \qquad (4.21)$$

In the equations for the heat transfer coefficient, the physical constants according to Eckert (Bibl.3) must be referred to the following temperature:

$$T^* = T_s + 0.5\,(T_w - T_s) + 0.22\,(T_e - T_s) . \qquad (4.22)$$

The heat, convectively transferred from the gas flow in the probe to the protecting tube, will be

$$Q_{c\,in} = \alpha_{c\,in} \cdot A_{wi}\,(T_{si} - T_{wi}) , \qquad (4.23)$$

where A_{wi} is the internal surface of the protecting tube, of a length ℓ_M.

The heat transfer coefficient $\alpha_{c\,in}$ is obtained from Hansen's formula (Bibl.3, 4) for fully formed laminar flow (Re < 2320) in pipes: /24

$$Nu = \frac{\alpha_{c\,in} \cdot d_i}{\lambda} = \left[3.65 + \frac{0.0668\,\dfrac{Re \cdot Pr \cdot d_i}{\ell_M}}{1 + 0.045\left(\dfrac{Re \cdot Pr \cdot d_i}{\ell_M}\right)^{2/3}} \right] \left(\frac{\eta_{T_{si}}}{\eta_{T_{wi}}}\right)^{0.14} , \qquad (4.24)$$

which is valid within the region $\dfrac{\ell_M}{Re \cdot Pr \cdot d_i}$ of 0.0001 to 10. The Reynolds number must be formed with the inside diameter d_i of the probe,

$$Re = \frac{w_i \cdot \rho_i \cdot d_i}{\eta} .$$

The reference temperature for the physical constants is the static temperature of the gas flow while the reference temperature for $\eta_{T_{wi}}$ is the wall temperature.

The thermal energy, transferred from the thermocouple to the internal wall of the protecting tube by radiation, when neglecting the heat dissipation, will read

$$Q_{th} = \alpha_p \cdot A \cdot \Delta T_{rad} , \qquad (4.25)$$

where

A = surface of the thermowires, of a length ℓ;

α_p = heat transfer coefficient along the thermowires.

Since the amount of heat which, within the protecting tube, flows from the inside toward the outside must agree with the wall temperatures, the following relation is valid in first approximation:

$$T_{wi} - T_{wo} = (Q_{c\ in} + Q_{r\ th}) \frac{1}{2\pi\ \ell_M\ \lambda_M} \cdot \ln \frac{d_{cr}}{d_i} \quad . \tag{4.26}$$

Using eqs.(4.21), (4.23), or (4.9) and (4.24) as basis and measuring the outer wall temperature T_{wo} of the protecting tube, the inner wall temperature T_{wi} can be calculated.

The thermal energy, radiated by the protecting casing toward the outside, will be

$$Q_r = \epsilon_M \cdot C_s \cdot A_M \left(\frac{T_{wo}^4}{100^4} - \frac{T_\infty^4}{100^4}\right) . \tag{4.27}$$

Here, it is assumed that the surrounding area A_∞, at a temperature of T_∞, is considerably larger than A_M.

In first approximation, the amount of heat given off by the protecting /25 tube by heat dissipation, is as follows:

$$Q_{diss} = \lambda_M \cdot A_{cr} \cdot (T_{wf} - T_0)\ a \tanh(a\ \ell_M), \tag{4.28}$$

with

$$a^2 = \frac{\alpha_0 + \alpha_i}{\lambda_M \cdot s} .$$

Here,

T_{wf} = wall temperature at the frontal area;

A_{cr} = cross-sectional area of the protecting tube;

T_0 = wall temperature at the height of the vents;

s = wall thickness of the protective casing, $s \ll (d_i + d_0)/2$;

α_0 = heat transfer coefficient on the outer surface of the protecting tube;

α_i = heat transfer coefficient on the inner surface of the protecting tube.

5. Test Data Correction for a Thermocouple in Transverse Flow /26

When using a probe of the type shown in Fig.4, in which the thermowires are perpendicular to the direction of gas flow, the test-data correction is obtained in a manner similar to that used for the static temperature probe.

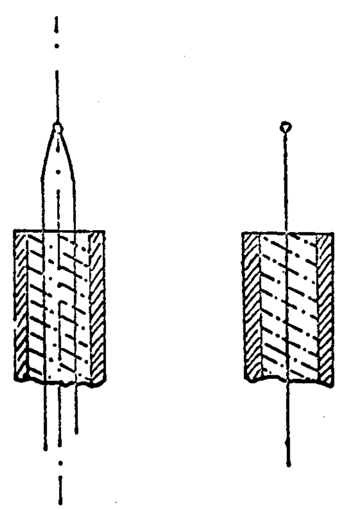

Fig.4 Thermocouple Arrangement; Direction of Gas Flow Perpendicular to the Wires

The velocity correction, at the Mach number Ma prevailing at the test point, is obtained in accordance with eq.(4.4). According to another report (Bibl.2), the following is valid for the recovery factor in the Mach-number region of 0.1 to 1:

$$r = 0.68 \pm 0.07 .$$

In a test setup, in which the surface of the thermocouple is small with respect to the area at a temperature T_∞ with which it is in radiative exchange, the radiation correction will read

$$T_{rad} = \frac{\epsilon_p \cdot C_s}{\lambda_p} \left(\frac{T_p^4}{100^4} - \frac{T_\infty^4}{100^4} - \epsilon_{tot} \frac{T_s^4}{100^4}\right) \tag{5.1}$$

The heat transfer coefficient α_p, in the Mach-number region of Ma = 0.015 to 0.9 and a Reynolds number of Re = 100 to 10,000 in accordance with Moffat (Bibl.2), is obtained by means of the relation

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$$Nu = \frac{\alpha_p \cdot d}{\lambda\ T_{tot}} = (0.44 \pm 0.06)\ Re^{0.5}. \tag{5.2}$$

Here, the Reynolds number and the Nusselt number refer to the wire diameter d. Equation (5.2) is valid for a wire diameter of about 0.2 to 1.5 mm. The reference temperature for the physical constants is the total temperature of the gas.

The correction for heat dissipation is obtained in a manner analogous to that used for the static temperature probe (see Section 4.4).

6. Compensation of the Radiation Error /28

In measurements with thermocouples made of electric resistance materials, a simple possibility exists for eliminating the radiation error, namely, feedback of the radiated energy to the thermocouple by resistance heating. The dependence of the radiated heat flux on the temperature is obtained as follows (Bibl.7): A thermocouple, heated by alternating current, is placed into a vessel which is sufficiently evacuated to almost completely prevent heat transfer by convection (about 10^{-3} torr). At a great immersion depth, i.e., at a depth sufficient to make the heat dissipation along the thermowires from the hot junction to the wall negligibly small, the heat dissipation in the vicinity of the hot junction takes place only by radiation. The supplied electric energy, consequently, must be in equilibrium with the radiated amount of heat.

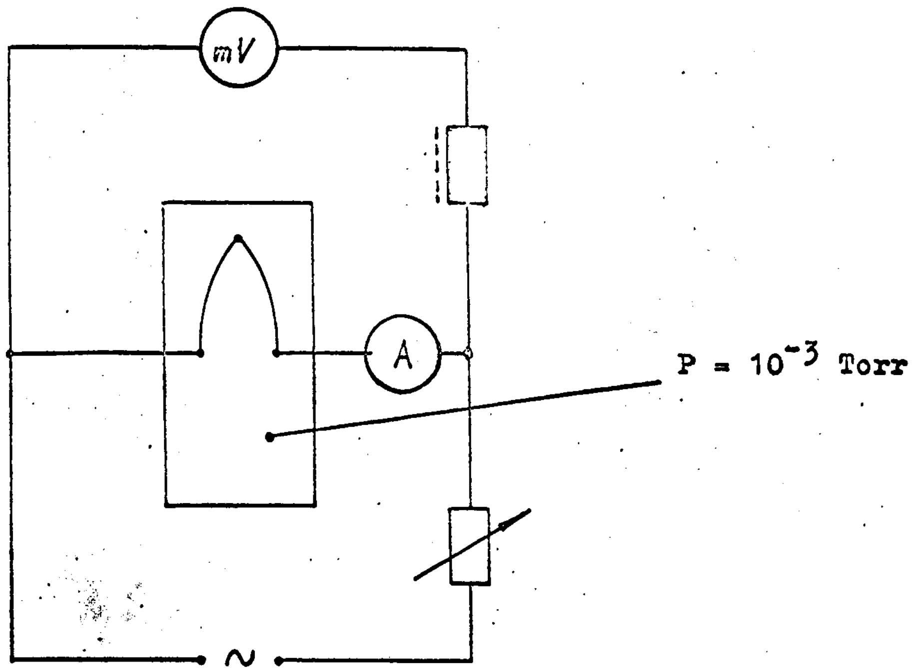

Fig.5 Circuit Diagram for Plotting the Characteristic T = f(I)

By measuring the thermal potential and the amperage of the heating current in the circuit diagram given in Fig.5, the compensation characteristic T = = f(I) will be obtained (Fig.6). /29

In temperature measurements in gases that are transparent to the heat rays, compensation of the radiation error will be obtained by adjusting the required heating-current strength in the manner required by the temperature reading of the thermocouple, in accordance with the characteristic shown in Fig.6. In this case, of course, we assume equal external radiation conditions, i.e., the spatial arrangement, the temperature, and the radiation properties of the surrounding areas must be the same as the conditions in the evacuated vessel.

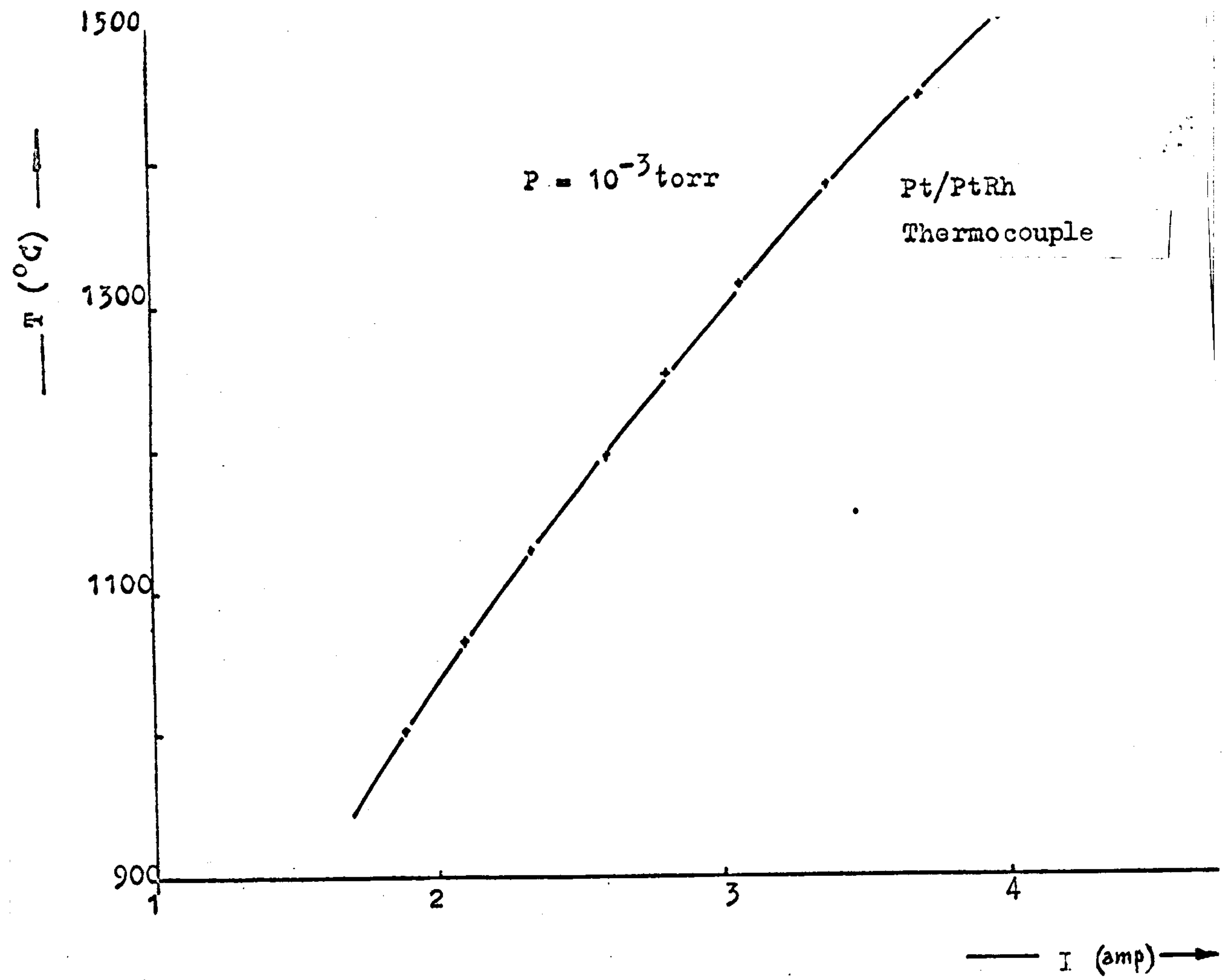

Fig.6 Temperature at the Hot Junction of the Thermocouple, as a Function of the Heating-Current Strength T = f(I)

7. Experiments Made /30

7.1 Experimental Test Setups

The experiments made were to determine the local gas temperature at the exit from a combustion chamber without fire tube. At an approximately constant state of the combustion chamber, the temperature of one profile point each was measured by means of the following probes:

a) Static temperature probe of Al_2O_3, using a PtRh/Pt thermocouple as data pickup (Fig.7a);

b) PtRh/Pt thermocouple in transverse flow (Fig.7b);

c) PtRh/Pt thermocouple in transverse flow, coated with Al_2O_3 (Fig.7c);

d) PtRh/Pt thermocouple in transverse flow, with compensation of the radiation error (Fig.7d);

e) Probe with cooled stem (Fig.7e).

The wall temperature of the static temperature probe was determined by a filament pyrometer. At the same time, the total pressure and the static pressure were measured at the test points, using cooled probes. In addition, the fuel-air ratio was determined from the weight rate of flow of air and fuel. The experimental results are shown in Fig.8.

The differing test results obtained with the various probes indicate that, without data correction, an accurate statement as to the temperatures prevailing at the test points is impossible. In order to decide whether the differences in the test data are due to instrument errors or to errors of method (for example, to catalytic effects), it is absolutely necessary to make data corrections.

7.2 <u>Data Corrections Made</u> /34

The data corrections were made as described in Section 4. Figure 8 shows the corrected values. For a given point, the calculated values are compiled in Table 1. In the correction of the test data, obtained with a static temperature probe, the determination of the Nusselt number was made in accordance with eq.(4.12a) of Warshawsky, since a blunt-weld thermocouple had been used. For the physical constants η and λ, the values for air were used; the quantities c_p and κ were determined in accordance with the temperature and composition of the

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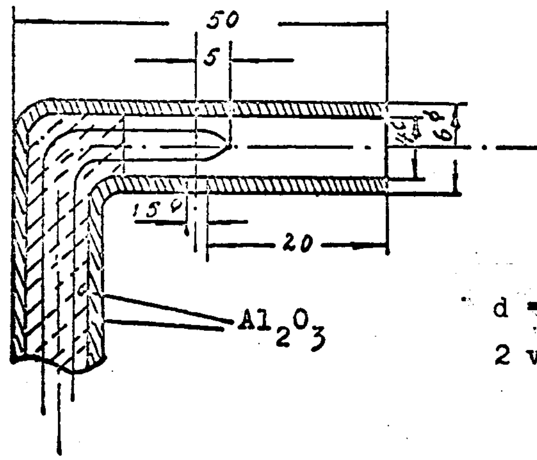
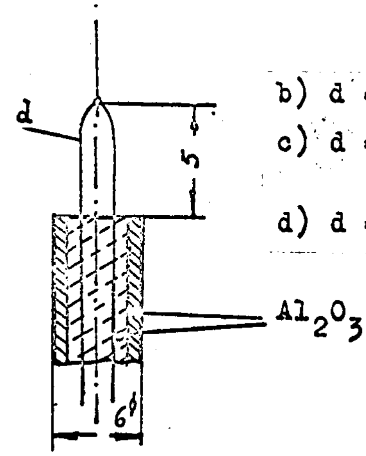


d = 0.5 mm
2 vents: d_h = 1.5 mm

Fig.7a Static Temperature Probe



b) d = 0.5 mm
c) d = 0.6 mm
(with Al_2O_3 coating)
d) d = 0.2 mm

Fig.7b - 7d Thermocouples in Transverse Flow

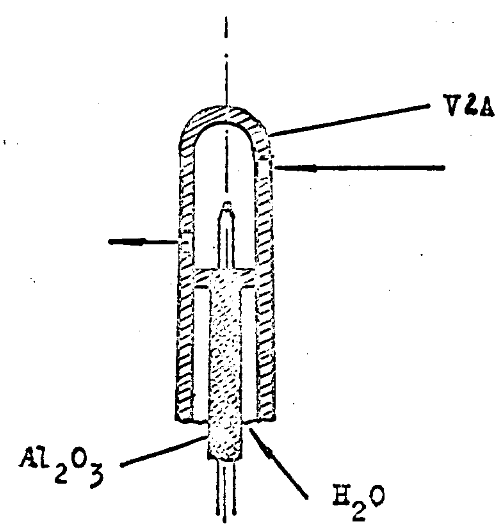


Fig.7e Thermocouple Probe with Cooled Stem

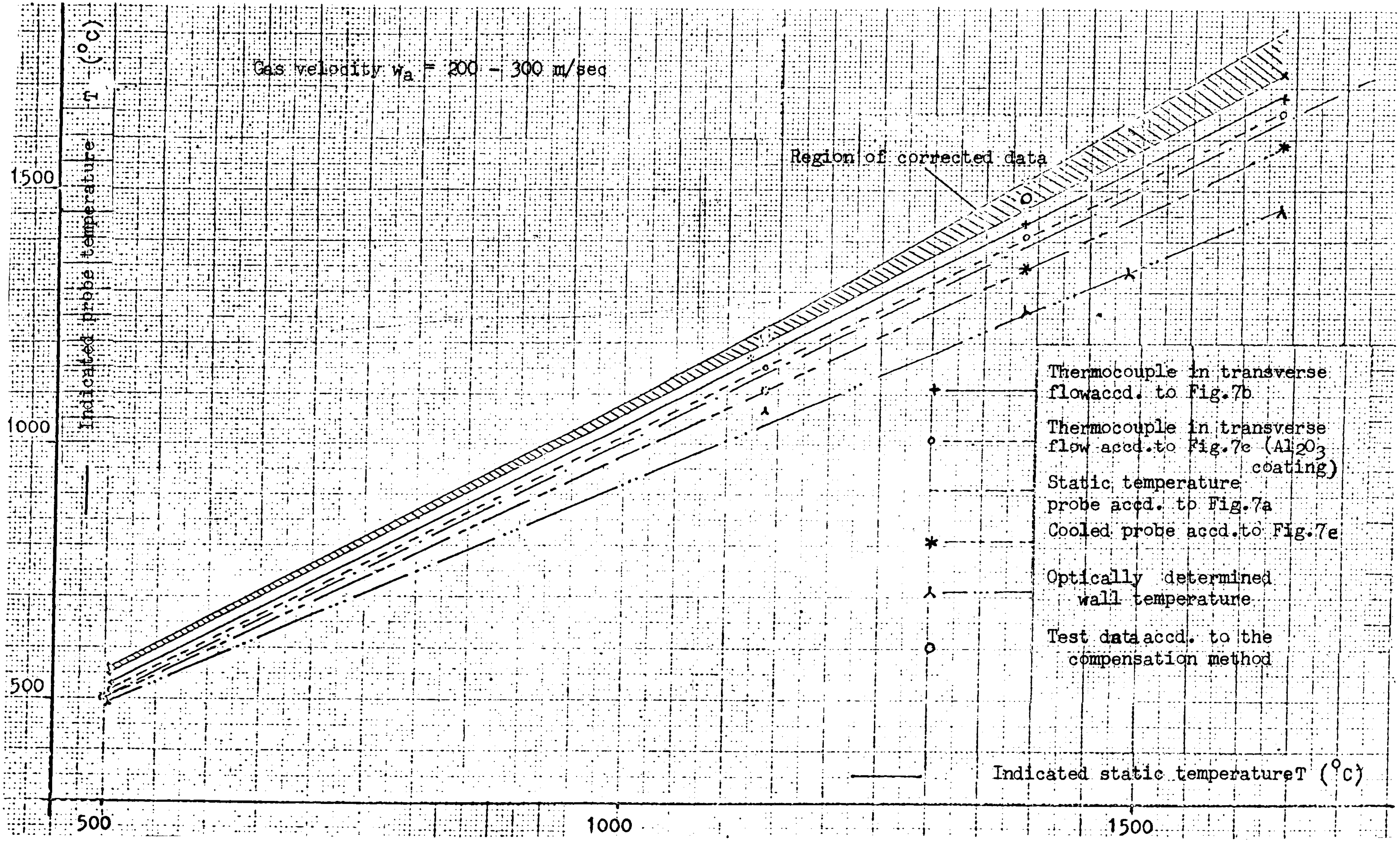


Fig.8 Local Temperature Measurements at the Exit from a Combustion Chamber without Fire Tube

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TABLE 1

TEST RESULTS AND DATA CORRECTIONS IN MEASUREMENTS WITH VARIOUS THERMOCOUPLE PROBES

Test Data		Static Temperature Probe (Fig.7a)	Thermocouple in Transverse Flow (Fig.7b)	Thermocouple in Transverse Flow, Coated with Al_2O_3 (Fig.7c)	
Indicated temperature	T_p [°K]	1910	1950	1920	$\varkappa = 1.313$
Probe-wall temperature	T_0 [°K]	≈ 1700	≈ 1750	≈ 1750	$\lambda_{T_{tot}} = 0.092 \left[\frac{kcal}{m\ hr\ deg}\right]$
Distance from hot junction, 5 m					
Static pressure	p_0 [$kp \cdot m^{-2}$]	10180	10180	10180	$\eta_{T_{tot}} = 6.55 \times 10^{-6} \left[\frac{kp \cdot s}{m^2}\right]$
Total pressure	p_{tot} [$kp \cdot m^{-2}$]	11020	11020	11020	$R = 29.27 \left[\frac{kp \cdot m}{kg \cdot deg}\right]$
Fuel-air ratio		$\frac{1}{21.22}$	$\frac{1}{21.22}$	$\frac{1}{21.22}$	$T_\infty = 300°K$
Total temperature (estimated) used in the calculation	T_{tot} [°K]	2020	2020	2020	$T_{w0} = 1730°K$

Calculated Values

	Test Data		Static Temperature Probe (Fig.7a)	Thermocouple in Transverse Flow (Fig.7b)	Thermocouple in Transverse Flow, Coated with Al_2O_3	
	Gas velocity at the test point	w_0 [$m \cdot sec^{-1}$]	298	298	298	T_s = 1985°K
	Reynolds number at hot junction	Re	114	430	520	ϵ_{Pt} = 0.18 (at 1950°K]
Calculated Values	Nusselt number at hot junction	Nu	2.08 ± 0.22	9.1 ± 1.2	10 ± 1.4	$\lambda_{Pt} = 70 \left[\frac{kcal}{m\ hr\ deg}\right]$
	Heat transfer coefficient on thermocouple	$\alpha \left[\frac{kcal}{m^2\ hr\ deg}\right]$	380 ± 40	1680 ± 230	1540 ± 210	$\epsilon_{Al_2O_3}$ =0.32 (at 1920°K)
	Velocity correction	ΔT_w [deg]	< 1	~ 10	~ 10	ϵ_{tot} = 0.026
	Radiation correction	$\Delta T_{r\ th}$ [deg]	100 ± 10	75 ± 10	135 ± 20	w_1 = 79 [$m \cdot sec^{-1}$]
	Dissipation correction	ΔT_{diss} [deg]	≪ 1	≪ 1	≪ 1	
	Total temperature	T_{tot} [°K]	2010 ± 10	2035 ± 10	2065 ± 20	

gas. In determining the emissivity ϵ_{tot} of the gas body (Bibl.4, 8), only the H_2O and CO_2 radiation was taken into consideration since the O_2 and N_2 radiation is negligible in the temperature range in question.

7.3 Heat Balance for the Static Temperature Probe

As a typical example, for the test data shown in Table 1 for which the correction was made, the heat balance of the static temperature probe will be given.

According to eq.(4.17), the energy supplied to the probe jacket by radiation is as follows:

$$Q_{r\ ex} = 0.026 \times 0.34 \times 4.96 \cdot \frac{19.85^4}{100^4} \cdot 20 \cdot \pi \cdot 6 \times 10^{-6} \approx 2.5 \frac{\text{kcal}}{\text{hr}} . \tag{7.1}$$

The heat transferred to the outside of the protecting tube [eq.(4.19)] will be

$$Q_{c\ ex} = 424 \cdot \pi \cdot 6 \times 20 \times 10^{-6} \ (1985 - 1730) \approx 41 \frac{\text{kcal}}{\text{hr}} . \tag{7.2}$$

Since the influence of friction is negligible at the relatively low gas velocity, the static gas temperature rather than the characteristic temperature T_e was used in the calculation.

The heat, transferred by convection to the inside of the protecting tube, is obtained in accordance with eq.(4.23) as follows:

$$Q_{c\ in} = 182 \cdot \pi \cdot 4 \times 20 \times 10^{-6} \ (2020 - 1740) \approx 12.8 \frac{\text{kcal}}{\text{hr}} . \tag{7.3}$$

The heat transferred by radiation from the thermocouple to the inside wall of the probe [eq.(4.25)] reads /35

$$Q_{r\ th} = 380 \times 2 \cdot \pi \cdot 0.5 \times 5 \times 10^{-6} \times 100 \approx 0.6 \frac{\text{kcal}}{\text{hr}} . \tag{7.4}$$

The thermal energy, radiated by the protecting tube toward the outside [eq.(4.27)] reads

$$Q_r = 0.34 \times 4.96 \cdot \pi \cdot 6 \times 20 \times 10^{-6} \frac{1730^4}{100^4} = 57 \frac{\text{kcal}}{\text{hr}},$$
$$\epsilon_{Al_2O_3} = 0.34 \text{ (at } 1730^\circ \text{K)}. \tag{7.5}$$

The heat given off by the protecting tube by dissipation [eq.(4.28)] reads

$$Q_{diss} = 56 \times 15.7 \times 10^{-6} \times 50 \cdot \tanh 14.7 \ll 1 \frac{\text{kcal}}{\text{hr}} \text{ (negligible)},$$
$$\lambda_M = 56 \frac{\text{kcal}}{\text{hr m deg}}; \; T_{wf} - T_0 \approx 50 \text{ deg}. \tag{7.6}$$

This will yield the following expression for the heat balance:

$$\frac{Q_{r\,ex} + Q_{c\,ex} + Q_{c\,in} + Q_{r\,th}}{Q_r + Q_{diss}} \approx 1\,. \tag{7.7}$$

7.4 Discussion of the Experimental Results

The values for the gas temperature of a profile point, measured with the three uncooled probes by the compensation method and subsequently corrected, lead to results that differ by only about 2%, as shown in Fig.8. This relatively good agreement, as also the result of the heat balance (Section 7.3), justify the assumption that no errors of method are present.

The presumable cause for the 2% deviation might consist of:

a) The restricted accuracy of the heat transfer calculations.

b) The restricted accuracy of the optical wall temperature determina- /36 tion when using a static temperature probe, due to the inhomogeneity of the Al_2O_3.

c) The inaccurate determination of the physical constants; this is true specifically for the emissivity ϵ of the probe materials which not only is dependent on the temperature but also is influenced greatly through possible contamination by the flame gases.

The calculated data corrections compiled in Table 1 indicate that, at the existing experimental conditions, only the radiation error is of significance. The dissipation error, because of the great immersion depth (80 mm) of the probes and the low heat conductivity of the Al_2O_3, is negligibly small for all three probes. As expected, the velocity error is negligibly small for the static temperature probes, and is still within the measuring accuracy in the case of thermocouples in transverse flow, at gas velocities of about 300 m/sec.

8. Summary /37

Within a temperature range of up to $2000^\circ K$, the determination of the local gas temperature can be performed with uncooled noble-metal thermels in tests on air-breathing engines. It must be taken into consideration that the test result, in the case of thermocouples coated with Al_2O_3, may be extensively falsified by errors of method, produced by the catalytic activity of the noble metals; such wrong results may occur specifically in measurements in a temperature range below the ignition temperature of the fuel-air mixture.

The instrument errors occurring in temperature measurements and produced by the gas velocity, heat dissipation, and radiation, can be defined by calculation. For a static temperature probe and a thermocouple in transverse flow, the possibilities of a data correction were described and demonstrated on a typical example. It was also shown that the corrected test data agree within an order of magnitude of 2%.

In addition, a method is described for eliminating the radiation error, by electrical feedback of the radiated energy to the thermocouple, by means of

resistance heating.

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